

# **Evolution of Earth Structure and Future Directions of 3D Modeling**

## **Asphericity, Anisotropy, and Anelasticity of the Mantle**

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### **Summary**

*It is no longer adequate to treat the Earth as a nearly spherically symmetric body with simple receiver, source and attenuation corrections tacked on. The aspherical velocity structure is now being determined by surface wave and body wave tomographic techniques and it has been found that heterogeneities are present at all levels. In the upper mantle the lateral variations in velocity are as large as the variations across the radial discontinuities. There is good correlation of velocity with surface tectonic features in the upper 250 km but the correlation rapidly diminishes below this depth. The focusing and defocusing effect of these lateral variations can cause large amplitude anomalies and these effects can be more important than attenuation.*

*Velocity variations in the mantle can be caused by temperature, mineralogy and anisotropy, or crystal orientation. The largest variations are caused by anisotropy and relaxation phenomena such as partial melting and dislocation relaxation. There is increasing evidence for anisotropy in the upper mantle and this must be taken into account in Earth structure modeling. Both azimuthal and polarization effects are important. Layering or fabric having a scale length less than a wavelength will show the statistical properties of the small scale structure. Global maps of heterogeneity and anisotropy show that if anisotropy is ignored the data will be mapped into a false heterogeneity. Azimuthal anisotropy compounds the off-great-circle problem.*

*The absorption band concept predicts that  $Q$  should be higher at short periods than at long periods and that there should be large lateral and radial variations in  $Q$ . The  $t^*$  controversy is probably related to shifts in the absorption band. If velocity is anisotropic then  $Q$  should be as well. Evidence is starting to suggest that there is a Love wave, Rayleigh wave discrepancy in  $Q$ , suggestive of  $Q$  anisotropy.*

## Introduction

Rapid progress has been made in the past few years in understanding departures of the Earth from an idealized spherically symmetric, isotropic and perfectly elastic body. Although much can be learned about the Earth, and the propagation of seismic waves, by intensive study of energy in a few narrow spectral bands some phenomena in these bands cannot be understood without information from a broader band of frequencies. Understanding the amplitudes of seismic waves, for example, requires knowledge of focusing, scattering, anelastic dispersion and mode coupling and these in turn require information about the Earth that cannot be obtained by narrow band studies of single wave types.

There is increasing evidence that the Earth is laterally heterogeneous on all scales and at all depths. This heterogeneity cannot be described with a standard set of travel time curves and station and source residuals. Station residuals are demonstrably affected by lower mantle as well as upper mantle heterogeneity. Station residuals, in fact, form the basis of recent tomographic studies of heterogeneity of the lower mantle and the upper mantle near sources and receivers. Surface waves provide a more uniform coverage of upper mantle heterogeneity, or asphericity, but with the present limited number of broad-band digital stations the lateral resolution is poor.

Evidence for upper mantle anisotropy is also increasing. Anisotropy introduces extra parameters into Earth structure studies and a large data base is required. It now appears, however, that some apparent structural complexity may be the result of attempting to satisfy data from the real Earth with isotropic models. Small scale structure, such as laminations, may also give rise to an apparent anisotropy, giving hope that even sub-wavelength complexities can be modeled.

The lateral heterogeneity of the upper mantle is such that significant off-great-circle propagation is expected. The resulting focusing and defocusing causes large amplitude anomalies.

The physics of anelasticity and the associated anelastic dispersion, *i.e.*, frequency dependence of velocity, is now fairly well understood. The shift of the absorption band with pressure, temperature and tectonic stress explains the large lateral and radial variations of  $Q$  and  $t^*$ . The anisotropy of anelasticity is one of the important problems to be resolved in understanding  $t^*$  and the amplitudes of seismic waves.

## Asphericity of the Mantle

The large variation in  $P$ - and  $S$ -residuals, or station corrections, and surface wave velocities are the most obvious manifestations of lateral heterogeneity.  $P$ -wave station residuals are now available for about 1000

global sites, and many more if local and regional arrays are considered. Travel-time anomalies were the basis of the early study by Dziewonski, Hager and O'Connell of the long wavelength heterogeneity of the lower mantle. Dziewonski and Anderson published new average travel times and station residuals for about 1000 stations using ISC data. For many stations they were also able to derive the  $\cos(2\theta)$  and  $\cos(4\theta)$  azimuthal terms (see Figs. 1, 2 and 3). Dziewonski has recently published a spherical harmonic description of asphericity of the lower mantle. His results show that a significant portion of the static and azimuthal station effect is due to structure in the lower mantle. This result indicates that the use of average travel time curves with source and receiver corrections is no longer adequate and that travel time anomalies are not entirely due to upper mantle effects. The next quantum jump is epicenter location accuracy which will involve a three-dimensional description of velocity throughout the Earth combined with ray-tracing from source to receiver.

A variety of tomographic body-wave techniques has been developed by Robert Clayton and his colleagues at Caltech. They have successfully inverted  $1.7 \times 10^6$  body wave arrival times to define the velocity in  $5^\circ \times 5^\circ \times 200$  km cells in the mantle. The lower mantle results have been used by Brad Hager and his colleagues to explain the long wavelength part of the geoid. The Clayton group has also used the large, dense southern California array (SCARLET) to obtain a detailed three-dimensional structure under this region down to about 600 km. Global and regional body-wave tomography is making it possible to model and understand heterogeneity on both a global and regional scale. The body wave tomographic results to date show that the regions between 670 and 800 km depth and  $D''$  are the most heterogeneous parts of the lower mantle. Velocity variations are of the order of several percent. The discovery of small scale velocity anomalies in the lower mantle explains the rapid lateral and directional dependence of station residuals and shows that detailed three-dimensional modeling of the mantle is required in order to improve epicentral locations. These small scale velocity anomalies may also help explain the variation of body wave amplitudes.

### Surface Wave Tomography

Several groups have recently analyzed large numbers of long-period digital seismograms with the aim of mapping the large scale heterogeneity and anisotropy of the upper mantle. Nakanishi, Tanimoto and Anderson have derived phase and group velocities over many hundreds of paths, for both Rayleigh waves and Love waves. Tanimoto is currently investigating the resolving power and uniqueness of this type of data. Nataf, Nakanishi and Anderson have inverted this data for heterogeneity and

polarization anisotropy of the upper mantle. Their model, NNAG, is shown in a series of figures at the end of this report. Present data is adequate to expand the heterogeneity to  $\ell = m = 6$  for all of the Earth, and  $\ell = m = 10$  for some regions. The average half-wavelength of resolvable features is about 2500 km. With a greatly expanded global digital network it should be possible to map heterogeneities as small as 500-1000 km. Portable digital arrays can be used to map even smaller structures using body wave and surface wave tomography.

Woodhouse and Dziewonski have used waveform matching techniques to study the dispersion of surface waves, including higher modes, over about 800 paths. They have inverted this information to obtain average shear wave velocities to depths of 670 km. In most regions their results are similar to the Nataf, Nakanishi, Anderson model. The differences are primarily due to different treatments of the crustal correction, the neglect of anisotropy, different choice of parameterizations, and different data sets. These differences should be understood in the next year but higher resolution must await the expanded global digital network.

Tanimoto and Anderson have recently determined the azimuthal variation of Love and Rayleigh waves on a global basis. The fast directions of Rayleigh waves appears to correlate with flow directions in the mantle. The azimuthal dependence of surface wave velocity will considerably complicate the ray tracing problem, including focusing and defocusing. There is no reason to expect that body wave propagation is immune from these anisotropic effects.

Lay and Kanamori have ray traced through model NNA6, showing the effects of focusing and defocusing. The amplitude anomalies due to geometric effects are much greater than expected from  $Q$  effects. Even relatively mild, long wavelength asphericity gives appreciable amplitude and off great circle effects.

## **Anisotropy**

The most studied effects of anisotropy include azimuthal variation of  $P_n$  and surface wave velocities, shear wave birefringence and polarization anisotropy. The minerals of the mantle are strongly anisotropic and are easily oriented by stress and flow. Variations in crystal orientation are more important than differences in temperature and composition in causing variation in velocity. Global data requires upper mantle anisotropy in order to explain Love and Rayleigh wave data and the  $\cos(4\theta)$  terms in station residuals. In a few areas differences in arrival times of  $SH$  and  $SV$  have been documented. In general  $SH > SV$  but this is reversed in regions of ascending and descending mantle flow as shown in studies by Regan, Anderson, Nataf and Nakanishi. This can be understood in

terms of orientation of olivine crystals. The large lateral variation in surface wave velocities are partly due to velocity variations caused by temperature and chemical differences and partly due to anisotropy. If anisotropy is ignored then erroneous velocity models will result.

If velocity is anisotropic then  $Q$  should be as well. There is some evidence that there is a Love-Rayleigh discrepancy in  $Q$ , just as there is in velocity. Physical mechanisms of attenuation, such as dislocation relaxation, are expected to be strongly anisotropic. If so, the commonly used expressions relating  $P$ -wave and  $S$ -wave  $Q$  are invalid.

### Body Wave Heterogeneity

Detailed body wave models now exist for such diverse tectonic regions as shields, tectonic, rise and old ocean. Velocities differ by as much as 10% in the upper 200 km and 4% between 200 and 670 km. These differences are much greater than can be explained by temperature alone and partial melting, dislocation relaxation or anisotropy are implied. The variations are similar to those inferred from surface wave tomographic results. We now need detailed attenuation and anisotropy studies in the same areas.

The use of  $SS$ ,  $PP$ , multiple  $ScS$  and  $P'P'$  precursors promise to provide detailed velocity and structural information in regions inaccessible to other phases. The power of these phases has been demonstrated particularly by Don Helmberger and Stephen Grand and their colleagues.

Mineralogical modeling of the new velocity models has led to the surprising result that the transition region is mainly clinopyroxene and garnet, rather than olivine. The olivine-spinel transition gives much greater velocity jumps than observed at 400 km. On the basis of seismic velocities the shallower mantle can be either peridotite or eclogite. Ridges and tectonic regions seem to be partially molten to depth of at least 300 km.

### Anelasticity

The effects of attenuation on velocity is now well understood and is incorporated into most recent seismic modeling. This effect reconciled body wave and free oscillation surface wave models. The frequency dependence of  $Q$  is still not understood. A frequency-independent  $Q$  is implausible but a mild frequency dependence over a narrow frequency range is permitted. Since absorption is likely to be a thermally activated relaxation phenomena the absorption band should shift with depth. High  $Q$  regions should have a strongly frequency dependent  $Q$ . Since temperature shifts the location of the band lateral variations in  $Q$  (or  $t^*$ ) should be accompanied by a change in the frequency dependence. Observed  $Q$ , or  $t^*$ , over a given path is the result of superposition of

absorption bands with different center or corner frequencies. The low- $Q$  parts of the path, of course, dominate. There should not be a single  $t^*$  or  $\tau_m$  for all locations and depths and attempts to model waveforms with one or two parameter models are doomed to failure. Scattering and mode conversion can contribute to apparent attenuation. Both a laterally- and depth-dependent absorption band  $Q$  model has not yet been fully exploited.  $\tau_m$  is exponentially dependent on temperature and therefore cannot be treated as a constant.

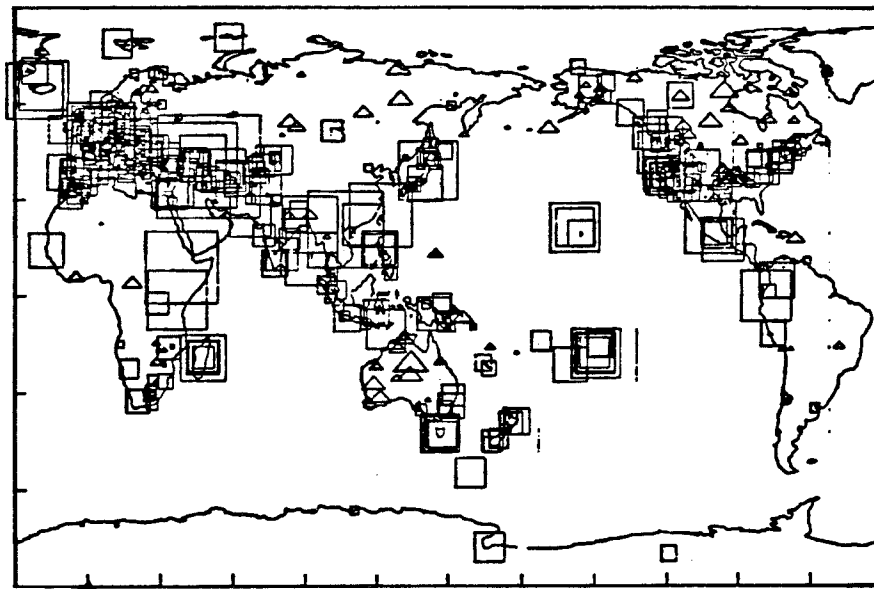
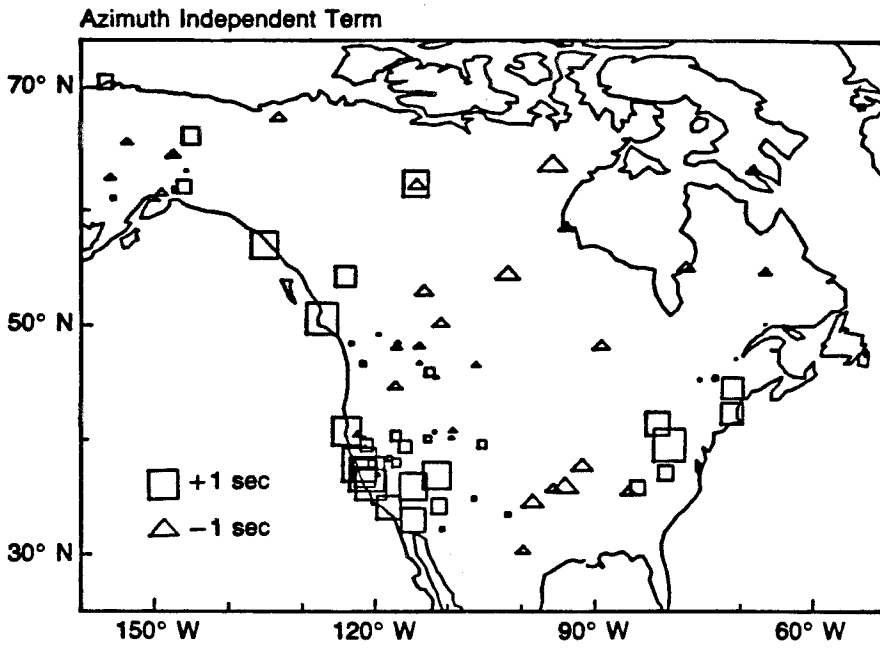
## Figures

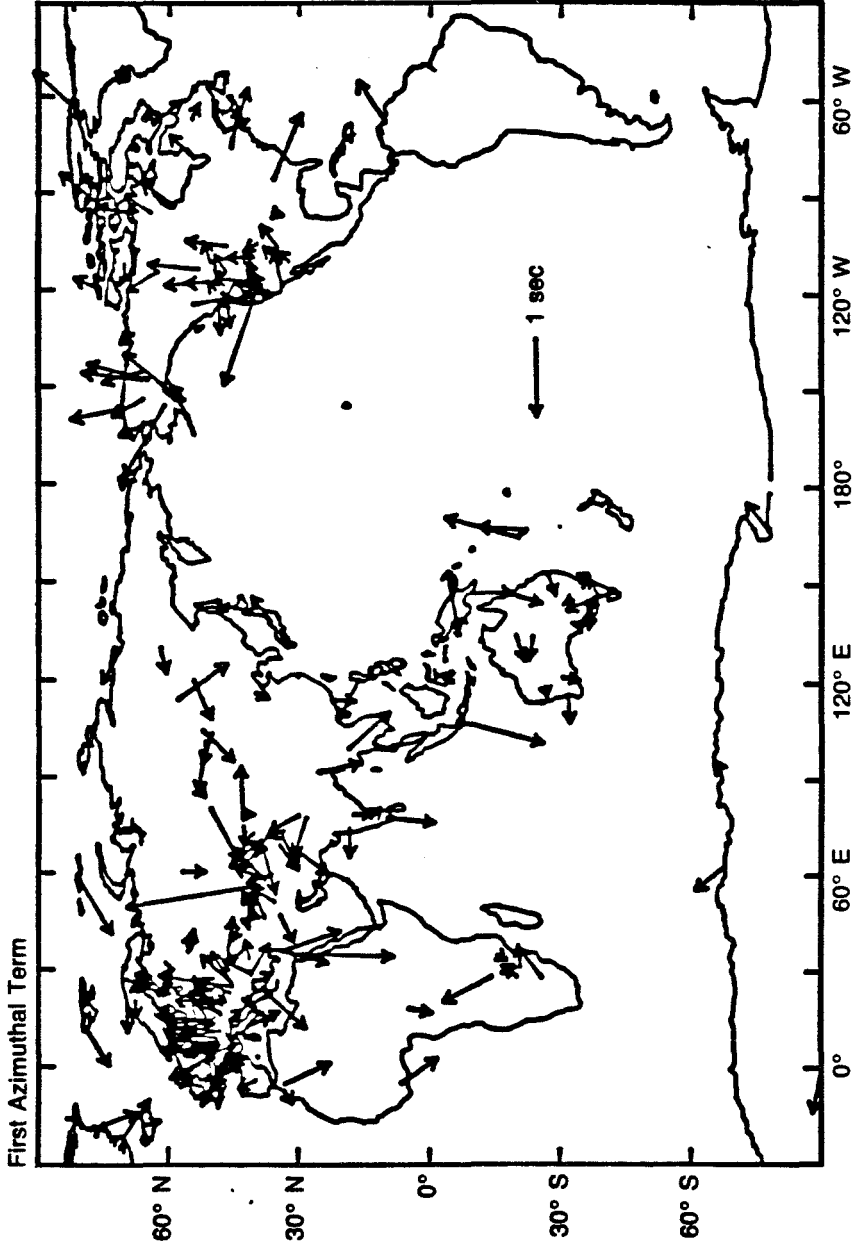
The figures give a series of maps at various depths and cross-sections of shear velocity ( $VSV$ ) and shear wave anisotropy ( $XI$ ). These parameters are combined in seismic flow maps and cross-sections. These maps and cross-sections are based on model NNA6 of Nataf, Nakanishi and Anderson (Geophysical Research Letters, 1984).

$XI$  is the anisotropy parameter  $(VSH)^2 / (VSH)^2 - 1$  and is positive for horizontal flow ( $a$ -axis horizontal for olivine).

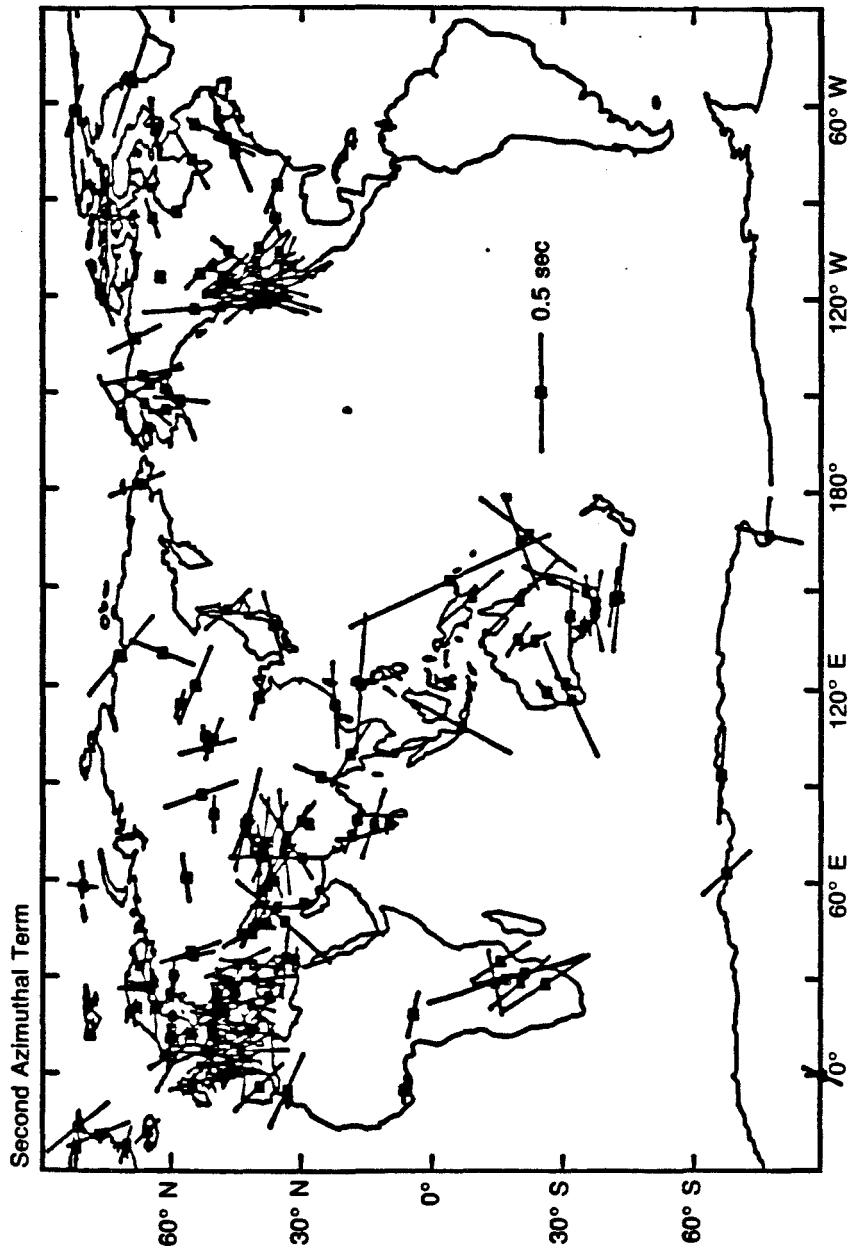
The azimuthal variation map is from Tanimoto and Anderson (Geophysical Research Letters, 1984) and is for 200 sec. Rayleigh waves. The lines are oriented in the fast direction. For comparison is the flow map of Hager and O'Connell.

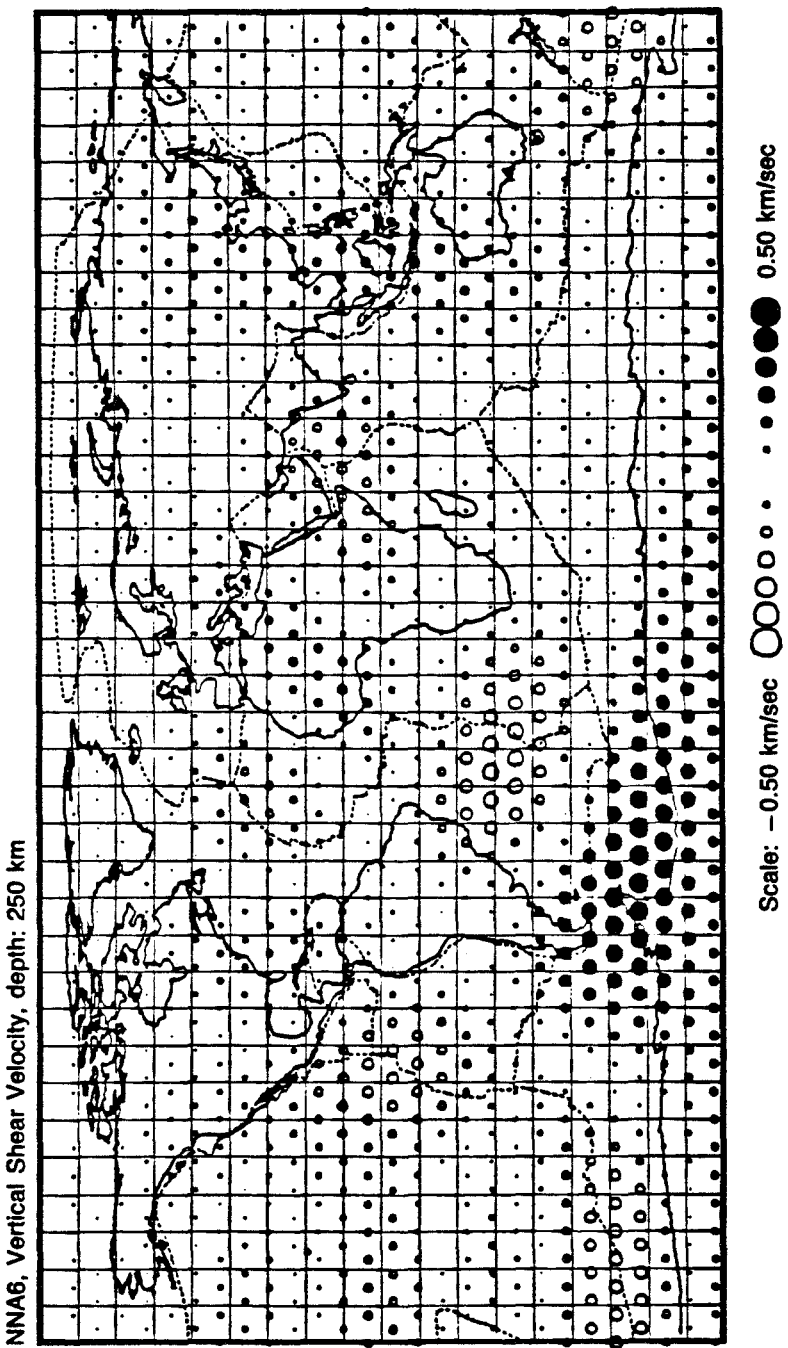
The station residual maps are from a study by Dziewonski and Anderson.

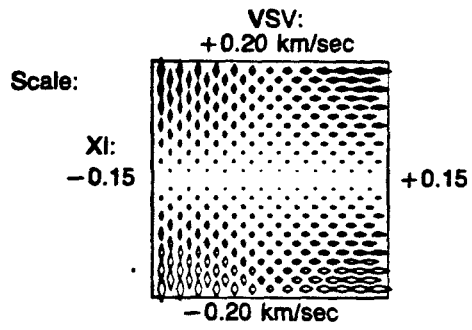




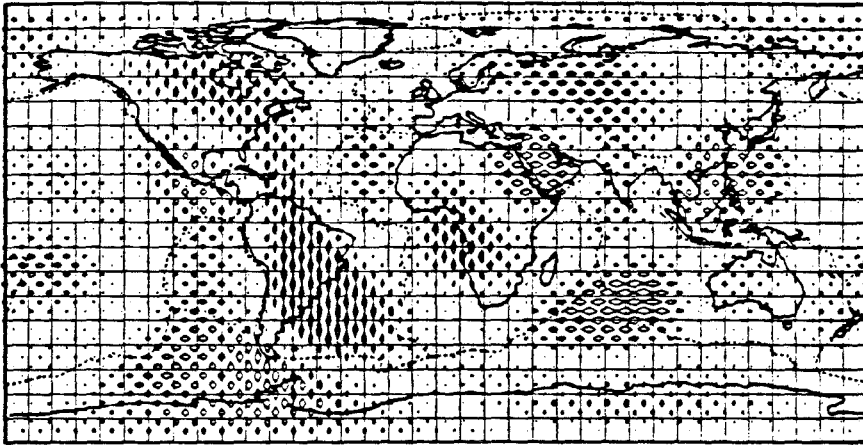


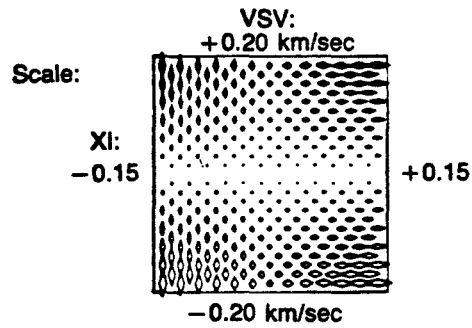




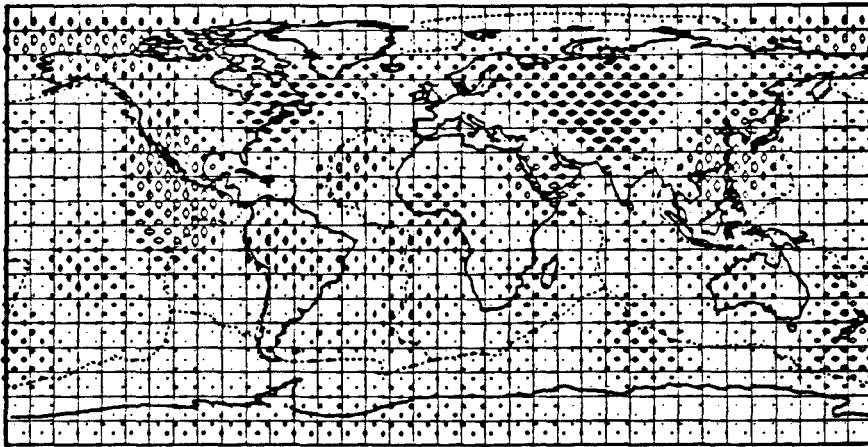


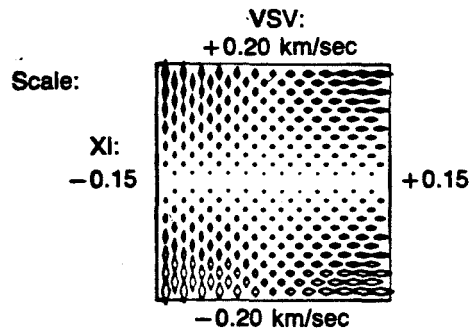
NNA6, Seismic Flow Map, depth: 100 km



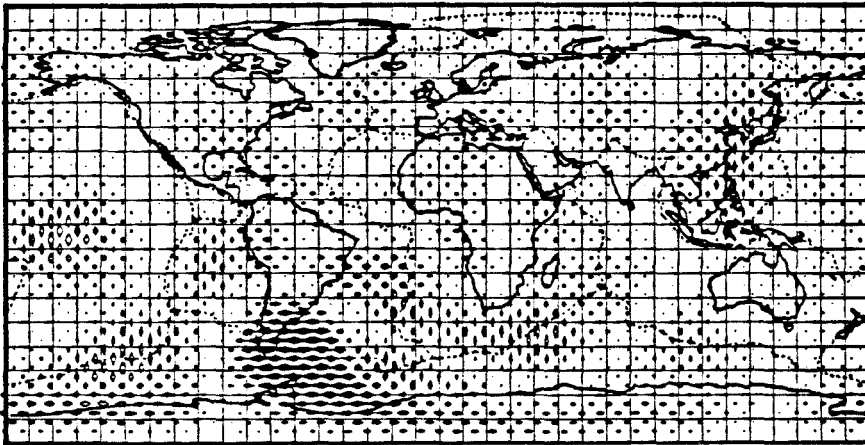


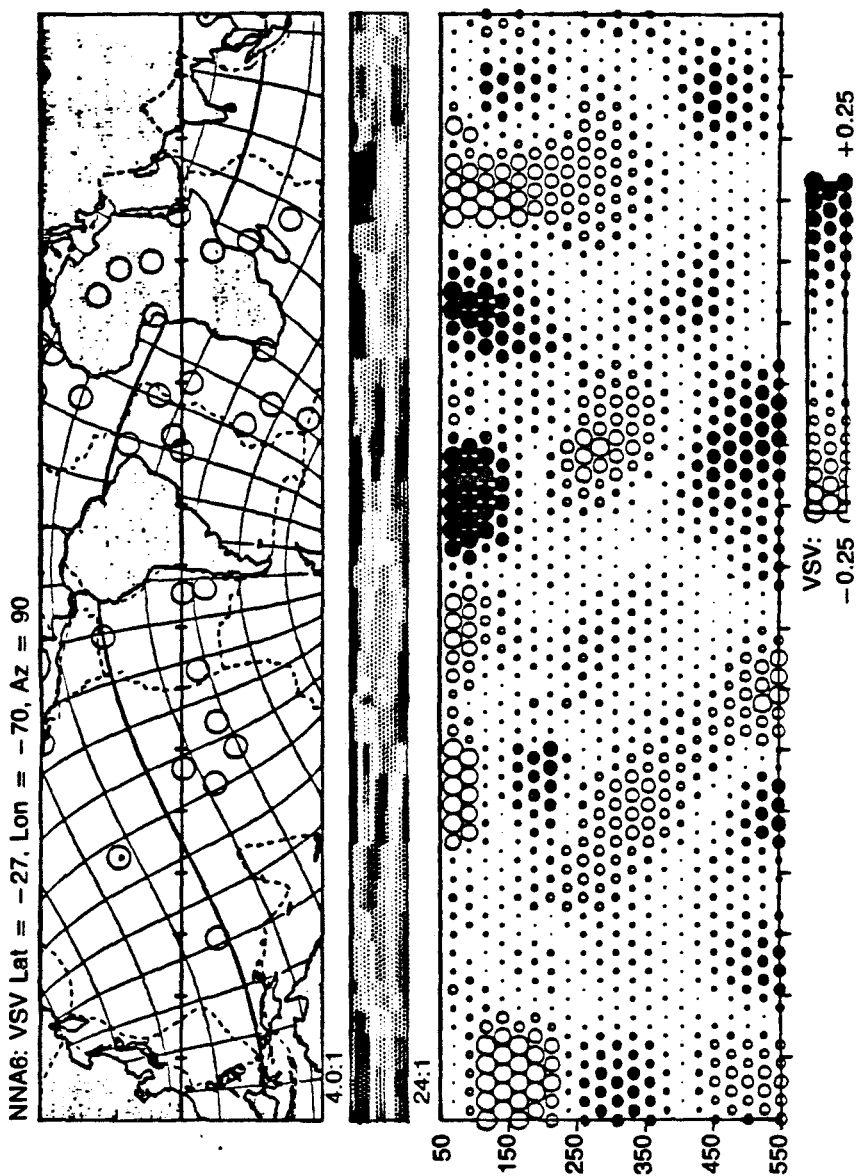
NNA6, Seismic Flow Map, depth: 160 km

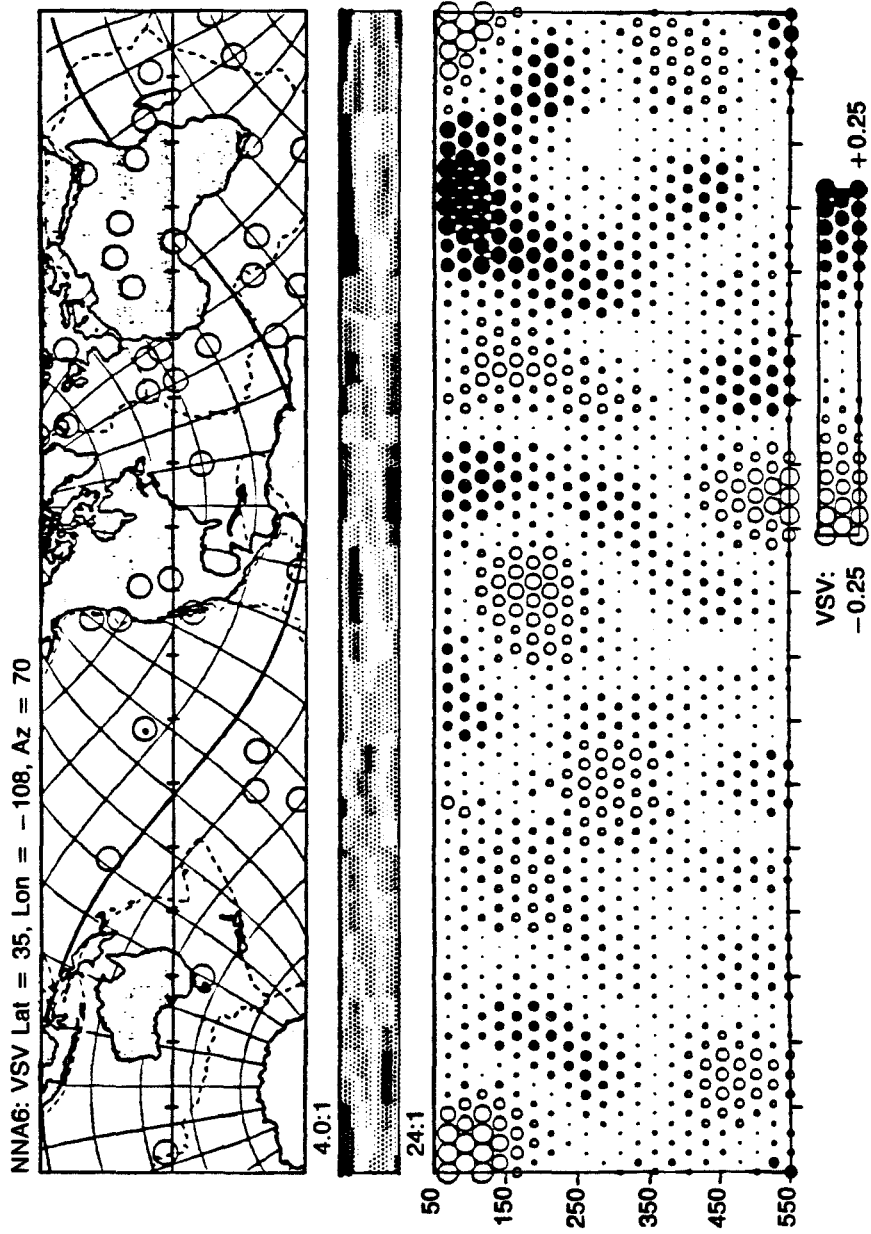


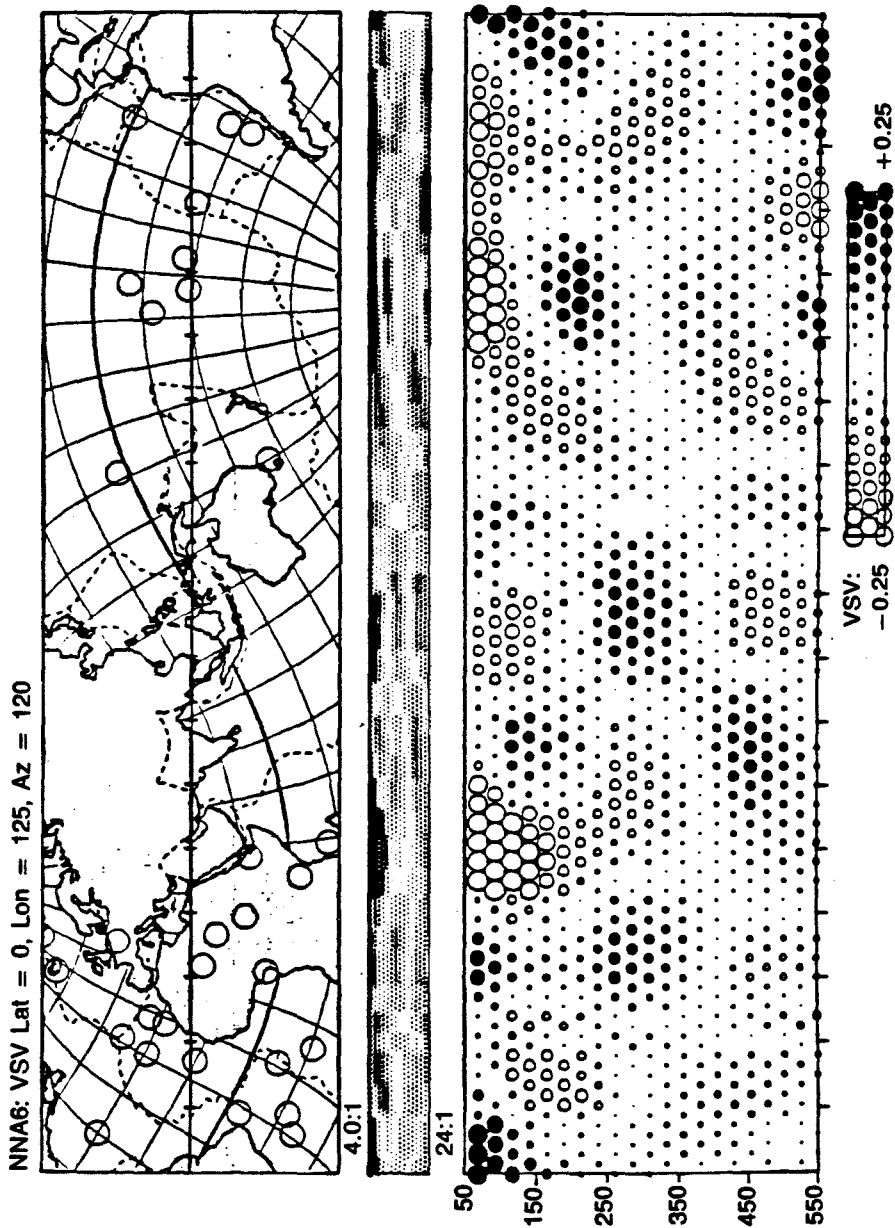


NNA6, Seismic Flow Map, depth: 340 km

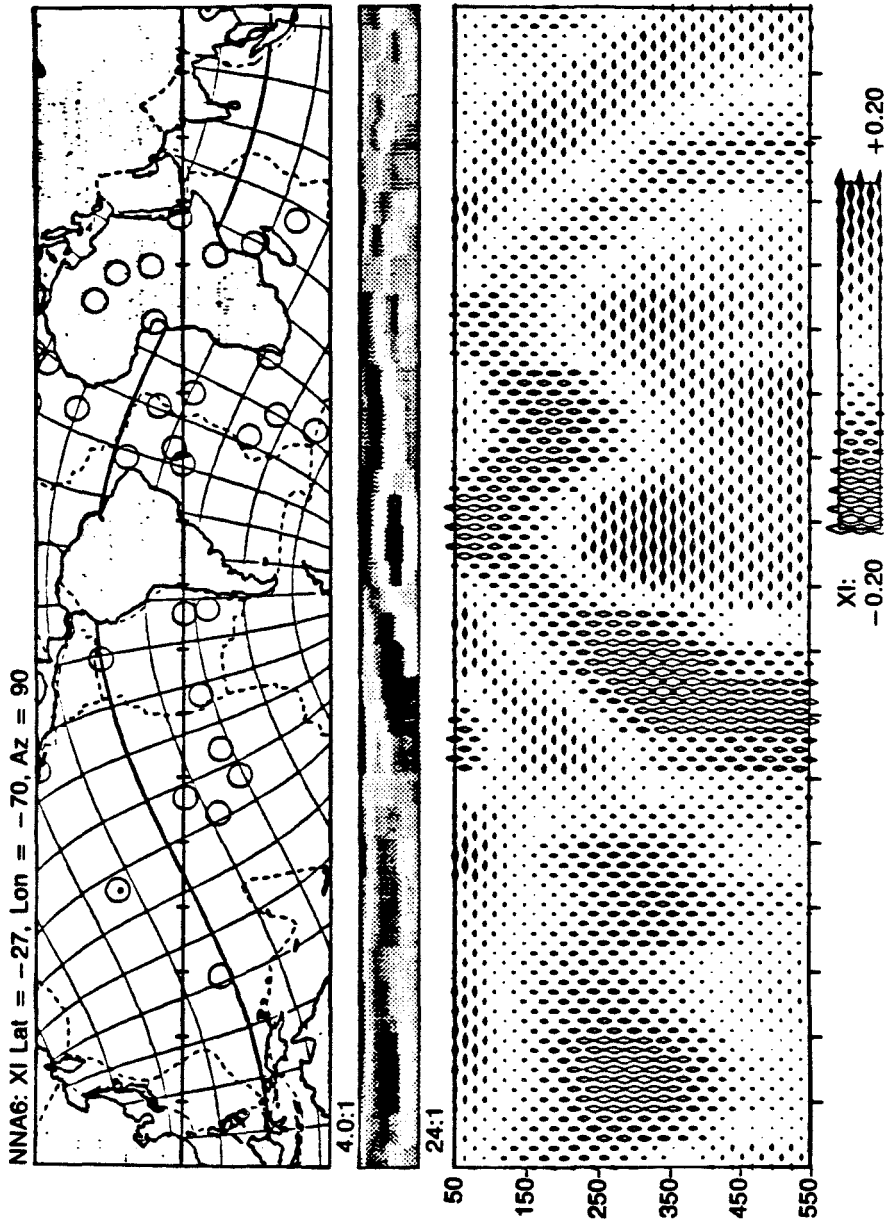


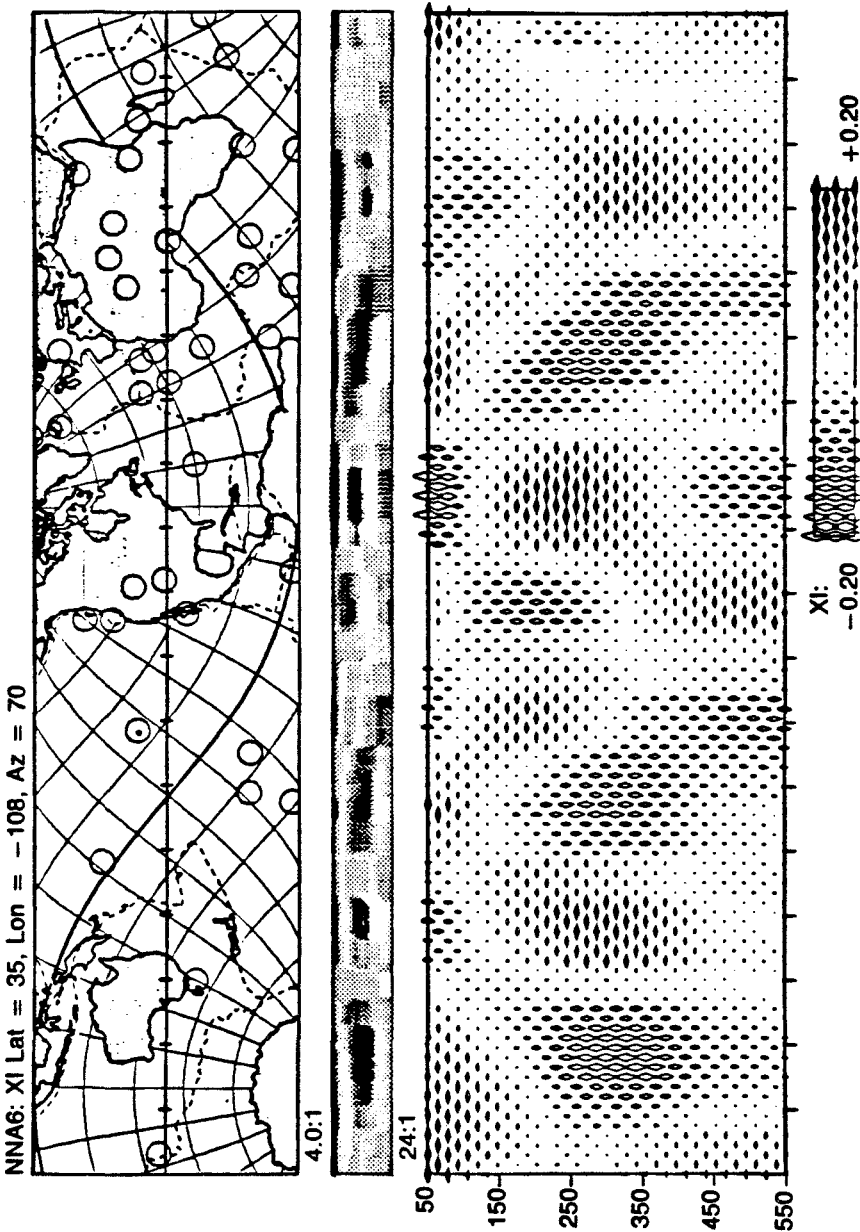


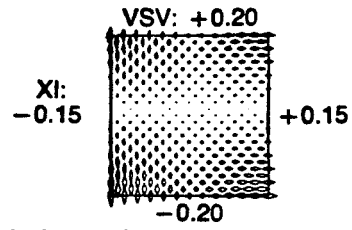




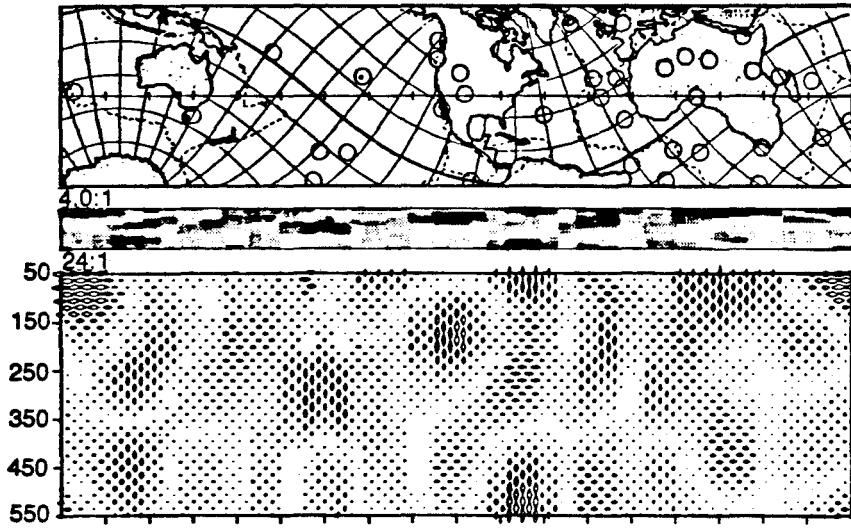


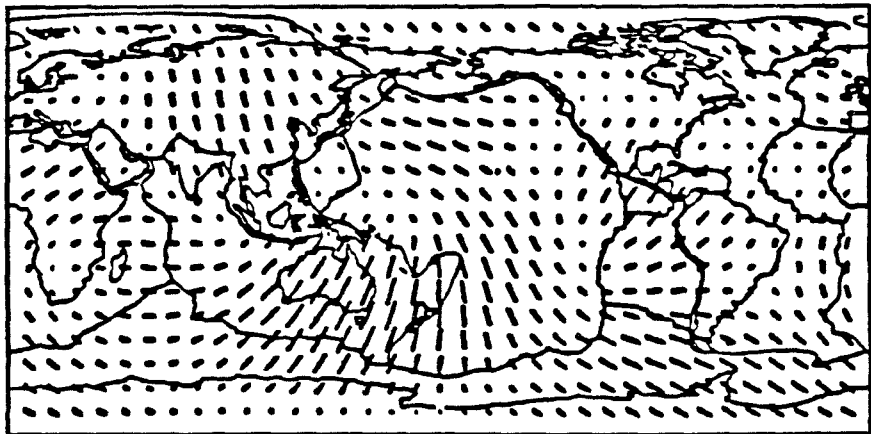




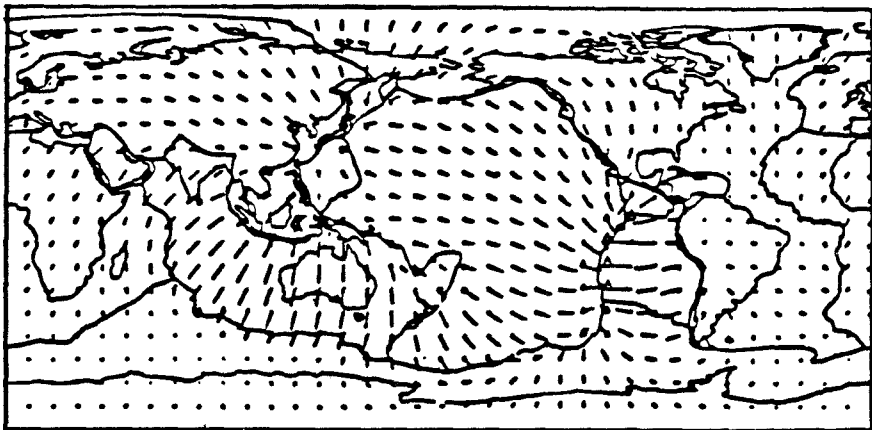


NNA6: Flow Map Lat = 35, Lon = -108, Az = 70





— 2 per cent



Velocities

260 km depth

Viscosity profile

$z/s$	$\eta$ (noise)
.99 - 1.00	$10^{23}$
.98 - .99	$10^{19}$
.89 - .98	$10^{22}$
.55 - .89	$10^{25}$

Cylindrical Equidistant

Scale = 75 MY

▲- upgoing

▼- downgoing